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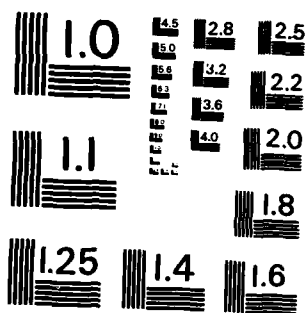
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report outlines design parameters for low-light-level imaging systems suitable for auroral and airglow research. Typical systems are considered, and comparisons of various detector systems presented. These considerations are relevant to ongoing instrument development for the NKC-135 Airborne Ionospheric Observatory.		

## Low Light Level Imaging Design

### 1. Introduction

Low-light-level imaging design involves evaluation of a number of variables that affect overall gain. Most systems include an image intensifier and some sort of recording device, such as film, a CCD array, or a TV camera. A list of factors that should be considered in design includes (though may not be limited to) input lens speed, filter transmission, spectral response of image intensifier, image intensifier gain, output phosphor spectral distribution, relay lens speed or fibre optics transmission, film speed (if used) or CCD or TV camera characteristics such as spectral response, sensitivity, and integration capability.

One normally has to rely on manufacturers' technical data for many of the above parameters, and these are often quoted in inconvenient or unfamiliar photometric units, often at an unspecified resolution. As a result, quoted "gains" or "sensitivities" of electro-optical devices may bear little relation to the specific problem being considered.

The purpose of this Report is to illustrate design calculations for a typical LLL imaging system that might be used in auroral or airglow research, and to provide appropriate explanations and definitions of the physical units one encounters in such calculations. ←

### 2. Definitions

2.1. Rayleigh: The unit of the *Rayleigh* is used widely in auroral and airglow research, and is somewhat equivalent to the radiometric term of *radiance*. Radiance is defined as the power leaving a surface per unit solid angle and unit projected area of that surface, and takes the units of watts per sq. cm per steradian,  $\text{Wm}^{-2} \text{sr}^{-1}$ . (This quantity is often called "surface brightness", an incorrect terminology because "brightness" is a perception sensation involving characteristics of the human eye.)

In auroral and airglow work, the important physical quantity is volume emission rate  $F$  in photons  $\text{cm}^{-3} \text{sec}^{-1}$ . If a "photon equivalent" of radiance,  $I$ , is obtained from measurements in units of photons  $\text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}$ , then

$$4\pi I = \int_0^{\infty} F(r) dr$$

is the emission rate integrated along the line of sight, and has the units photon  $\text{cm}^{-2} (\text{column})^{-1} \text{sec}^{-1}$ .

The Rayleigh is defined as an *apparent emission rate* of  $10^6$  photons  $\text{cm}^{-2} \text{column}^{-1} \text{sec}^{-1}$ . The "apparent" refers to the fact that no allowance has been made for scattering or absorption.

2.2. Lumen: Radiometric terms apply anywhere in the electromagnetic spectrum, and involve real physical quantities. Photometric terms, of which *lumen* is one, apply only in the visible part of the spectrum, and relate to the visual effectiveness of the light i.e. the sensation resulting in the human visual system. Conversion of radiometric to photometric units always involves the relative visibility of light at the wavelength being considered, the luminous efficiency (or photopic) curve (Figure 1). The ratio of any photometric unit to its radiometric equivalent is called luminous efficacy,  $e_\lambda$  (Table 1). The peak at 555 nm is the wavelength to which the "average eye" is most sensitive.



Table 1 STANDARD LUMINOUSITY DATA

Wavelength	Luminous efficacy	Wavelength	Luminous efficacy
410	0.001	570	0.952
420	0.004	580	0.870
430	0.012	590	0.757
440	0.023	600	0.631
450	0.038	610	0.503
460	0.060	620	0.381
470	0.091	630	0.265
480	0.139	640	0.175
490	0.208	650	0.107
500	0.323	660	0.061
510	0.503	670	0.032
520	0.710	680	0.017
530	0.882	690	0.008
540	0.954	700	0.004
550	0.993	710	0.002
560	0.996	720	0.001

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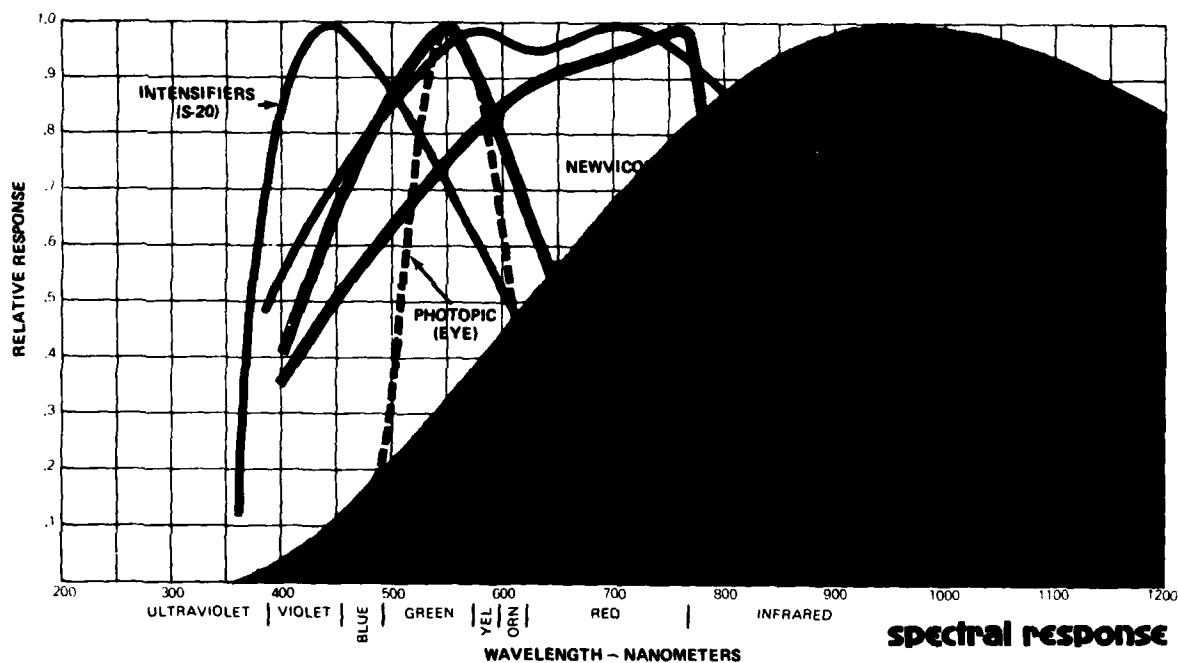
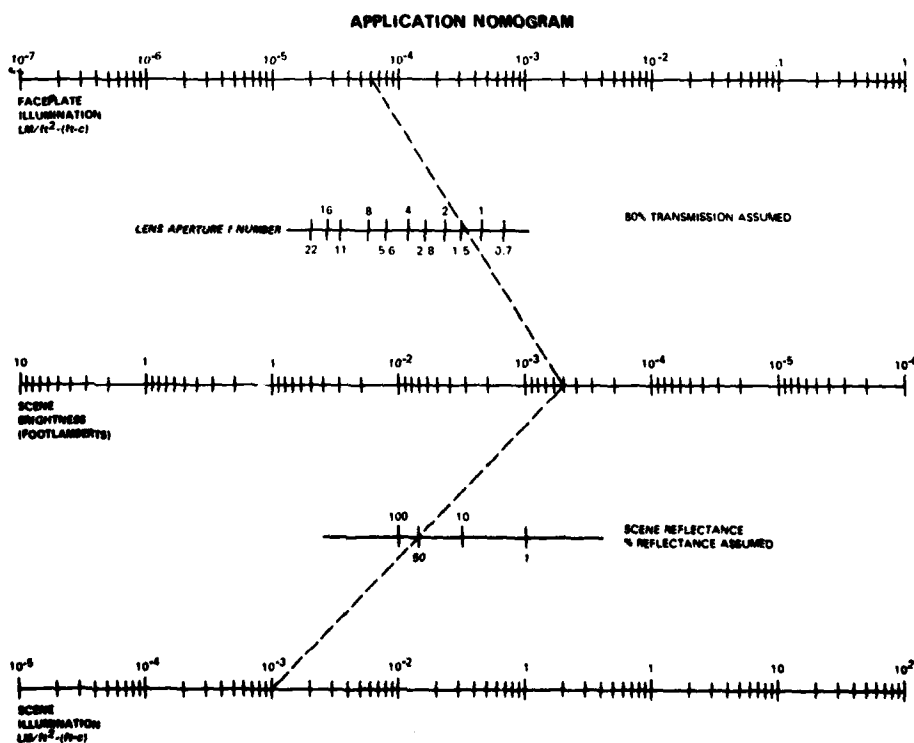


Fig. 1



Example: It is an overcast night, and the scene illumination is considered to be approximately  $10^{-3}$  lm/ft<sup>2</sup>. Assuming a scene reflectance of 80%, a dotted line is drawn to the scene brightness line. This tells you that scene brightness is  $5 \times 10^{-2}$  ft. Using an f/1.4 lens on the television camera, the dotted line is projected to the faceplate illumination line. You now know that you have  $5 \times 10^{-2}$  faceplate illumination lm/ft<sup>2</sup>. Referral to data sheets of television cameras will now isolate those that will permit you to televise from the area you have selected.

Figure 2

The radiometric unit of *power*, or energy transferred per unit time, is the *watt*:  $1 \text{ W} = 1 \text{ joule sec}^{-1}$ . The photometric equivalent, *luminous power*, is the quantity of radiant power that produces a visual sensation to a human observer, and has the units of lumens.

At a wavelength of 555 nm,  $1 \text{ lumen} = \frac{1}{680} \text{ W}$ , or  $1 \text{ W} = 680 \text{ lumen}$ . At any other wavelength, this conversion must be multiplied by the luminous efficacy. For example, at 630 nm the luminous efficacy is 0.265 so  $1 \text{ W} = 680 \times .265 = 180 \text{ lumen}$ .

2.3. Illuminance: The radiometric term for radiant power incident on a surface is *irradiance* in  $\text{W m}^{-2}$ . The photometric equivalent is *illuminance*,  $E$ , which is the luminous power incident on a surface, in  $\text{lumen m}^{-2}$ , or *lux*.

The input power incident on an image intensifier or TV camera tube is usually specified by the manufactures in *foot candles*. This is an antiquated unit whose use should be discouraged, and is defined by

$$\begin{aligned} 1 \text{ ft. candle} &= 1 \text{ lumen ft}^{-2} \\ &= 10.76 \text{ lumen m}^{-2} \\ &= 10.76 \text{ lux} \end{aligned}$$

2.4. Luminance: The radiometric term for radiant power leaving a surface is radiance in  $\text{W m}^{-2} \text{ sr}^{-1}$ . The photometric equivalent is *luminance*,  $L$ , which is the luminous power leaving the surface, in  $\text{lumen m}^{-2} \text{ sr}^{-1}$ .

The output power leaving an image intensifier is usually specified by the manufactures in *foot-lamberts*. This is an antiquated unit whose use should be discouraged, and is defined by

$$\begin{aligned} 1 \text{ ft. lambert} &= \frac{1}{\pi} \text{ lumen ft}^{-2} \text{ sr}^{-1} \\ &= 3.43 \text{ lumen m}^{-2} \text{ sr}^{-1} \end{aligned}$$



2.5. Nomogram: A useful nomogram relating illuminance, luminance, and LLL camera parameters, is given in Figure 2.

2.6. Conversion to Rayleighs: To find the Rayleigh equivalents of the above units, two conversions must be made, viz: from photometric units to radiometric (energy) units, and then from energy units to photon units.

The energy associated with a photon of a given wavelength is given by:

$$E_{\lambda} = \frac{hc}{\lambda}$$

$$= \frac{1.986 \times 10^{-9}}{\lambda} \text{ erg photon}^{-1}, \text{ with } \lambda \text{ in nm.}$$

$$\begin{aligned} \text{Therefore 1 ft. candle} &= 1 \text{ lumen ft}^{-2} \\ &= 1.07 \times 10^{-3} \text{ lumen cm}^{-2} \\ &= \frac{1.07 \times 10^{-3}}{680 \times e_{\lambda}} \text{ W cm}^{-2} \\ &= \frac{1.07 \times 10^{-3}}{680 \times e_{\lambda} \times E_{\lambda}} \times 10^7 \text{ photons cm}^{-2} \text{ sec}^{-1} \\ &= 7.92 \times 10^9 \times \frac{\lambda}{e_{\lambda}} \text{ photons cm}^{-2} \text{ sec}^{-1} \quad * \\ 1 \text{ ft. lambert} &= \frac{1}{\pi} \text{ lumen ft}^{-2} \text{ sr}^{-1} \\ &= 2.52 \times 10^9 \times \frac{\lambda}{e_{\lambda}} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \quad * \\ &= \frac{4\pi \times 2.52 \times 10^9}{10^6} \times \frac{\lambda}{e_{\lambda}} \text{ Rayleighs} \\ &= 3.17 \times 10^4 \times \frac{\lambda}{e_{\lambda}} \text{ Rayleighs} \end{aligned}$$

For example, at 530 nm

$$\begin{aligned} 1 \text{ ft. candle} &= 4.87 \times 10^{12} \text{ photons cm}^{-2} \text{ sec}^{-1} \\ 1 \text{ ft. lambert} &= 1.55 \times 10^{12} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \\ &= 1.95 \times 10^7 \text{ Rayleighs} \end{aligned}$$

### 3. The Illuminating Light Source

When manufacturers quote an input sensitivity of an image intensifier or TV camera tube, they usually speak of a "usable picture" at a certain number of foot candles. There is often no specific definition of "usable picture", but one can probably assume it means a signal/noise ratio of ~2. An even more serious defect in manufacturer's specification sheets is that they often do not specify the light source used when obtaining sensitivities in foot candles. Unless specified otherwise, one can usually assume the light source used is a ~75W incandescent light bulb i.e. a tungsten source with a color temperature of 2854°K, closely equivalent to the Standard Illuminant A defined by the International Commission of Illumination (Figure 1).

Such a source has a spectral distribution that peaks in the near infrared, well outside the visible region. Hence if the photocathode has appreciable red and near infrared response, the gain figures that result may be quite unrealistic when one is considering the visible region. This is because when the illuminance is calculated from such a source, the irradiance is weighted by the luminous efficacy. Thus the peak energy outside the visible region does not contribute significantly to the illuminance, but does contribute to photocathode response. Table 2 lists data required to estimate the tube response at a particular wavelength compared to that quoted by the manufacturer, for a typical S20/25 extended red photocathode (Figure 1).

It may be seen from column (5) in Table 2 that half of the tube response results from wavelengths above the visible region (> 700 nm), whereas none of this wavelength region contributes to the illuminance (column 4).

The *gain* of an image intensifier is defined by

$$\text{gain} = \text{luminance out} / \text{illuminance in}$$

Table 2

$\lambda(\text{nm})$	(1) Relative watts 2854°K	(2) Luminous Efficacy	(3) Typical Sensitivity mA/watt	(4) (1)x(2)	(5) (1)x(3)
350	.016	0.	75.	.0	1.2
400	.050	0.001	88.	.0	4.4
450	.115	0.038	89.4	.004	10.2
500	.200	0.323	84.	.065	16.8
550	.325	0.993	75.	.313	23.6
600	.440	0.631	65.	.278	28.6
650	.630	0.107	55.	.067	34.6
700	.680	0.004	45.	.003	30.6
750	.780	0.	34.	.0	26.5
800	.860	0.	23.	.0	19.8
850	.920	0.	13.	.0	12.0
900	.970	0.	5.	.0	4.8
950	.990	0.	1.	.0	1.0

If one imagines a perfect transmitting diffuser, with no transmission losses and a Lambertian output, then 1 ft. candle incident illuminance will give 1 ft. lambert output luminance, and we can define this as a *gain* of 1. This is the concept of gain that is used when tube manufacturers quote their figures, except there are completely different input and output spectral shapes. Consequently the quoted gains are difficult to relate to any meaningful physical quantity such as photon gain at a specific wavelength.

For example, the information in Table 2 allows one to calculate that for equal illuminance onto the image intensifier (ft. candles), the gain at 550 nm would be 25% of that for a 2854°K source. On the other hand, for equal irradiance ( $\text{W m}^{-2}$ ), the "gain" at 550 nm would be 238% of the gain for the 2854°K source.

To derive the associated *photon gain*, defined by

$$\text{photon gain} = \frac{\text{photons cm}^{-2} \text{ sec}^{-1} \text{ (incident on photocathode)}}{\text{photons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \text{ (leaving output phosphor)}}$$

the spectral shape of the 2854°K light source (illuminant A), the photocathode spectral response, and the phosphor spectral output must all be considered. Suffice to say that in the 500-550 nm region, the photon gain is typically 25% of the quoted manufacturer's gain, and varies at other wavelength with the quantum efficiency of the cathode. This "photon gain" is similar to the "blue gain" quoted by some manufacturers, which is obtained by placing a pale blue filter (Corning #9788) in front of the 2854°K light source.

#### 4. A Typical System

##### 4.1 Faceplate Illuminance:

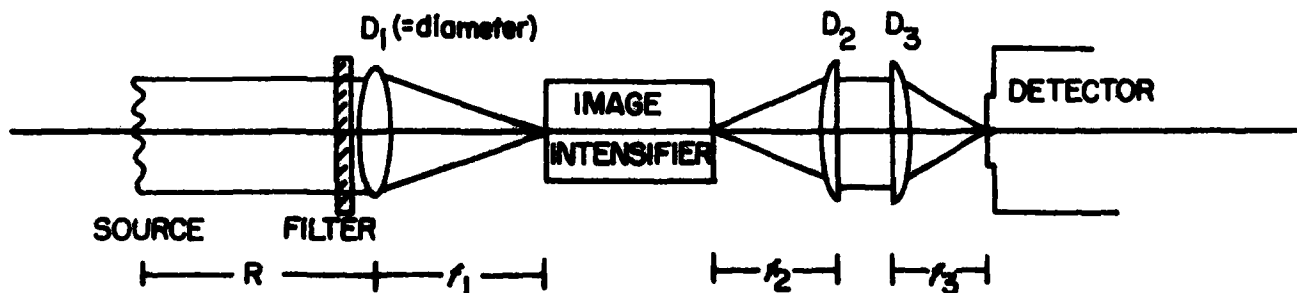


Figure 3

$$1 R = 10^6 \text{ photons cm}^{-2} \text{ column}^{-1} \text{ sec}^{-1}$$

$$= \frac{10^6}{4\pi} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$$

$$\text{No. steradians subtended by lens} = \frac{\pi D^2}{4R^2}$$

$$\text{Image magnification (area)} = \frac{f^2}{R^2}$$

Therefore, No. photons incident on 1 cm<sup>2</sup> of faceplate of image intensifier

$$= \frac{10^6}{4\pi} \cdot \frac{\pi D_1^2}{4R^2} \cdot \frac{R^2}{f_1^2} \text{ sec}^{-1}$$

$$= \frac{10^6}{16F_1^2} \text{ sec}^{-1} \text{ where } F_1 = F \text{ no. of lens \#1.}$$

#### 4.2 Relay Lenses:

Solid angle subtended by lens =  $\frac{\pi D^2}{4f^2}$

Area magnification =  $\frac{f_2^2}{f_3^2} (D_3 > D_2)$

If L is the output luminance of the image tube, then number of photons collected

$$= L \times \frac{\pi D_2^2}{4f_2^2} \cdot \frac{f_2^2}{f_3^2} = \frac{\pi D_2^2 L}{4f_3^2}$$

Loss factor =  $\frac{\text{No. photons collected}}{\text{Total emitted (assumed Lambertian)}}$

$$= \frac{D_2^2}{4f_3^2}$$

If both lenses are F1.2, then

Loss factor = .174

Note that an alternate means of coupling would be directly by fibre optics. The acceptance cone angle for a typical fibre optics coupler is ~41°. This corresponds to a numerical aperture of 0.66, and compared to the total light emitted (assumed Lambertian),

Loss factor = (numerical aperture)<sup>2</sup>

$$= 0.44$$

Thus fibre optics is some 2.5 times more efficient as a coupler than a pair of F1.2 relay lenses.

4.3.1. Assume: input lens	F 1.2
relay lenses	F 1.2
filter transmission T	0.75
transmission t (relay lenses)	0.75
intensifier gain	$5 \times 10^4$ ("manufacturer's gain" for 2nd Gen. intensifier)
output phosphor	P20 (530 nm peak)
input $\lambda$	530 nm

Then for 1 K of source

$$\begin{aligned} \text{No. photons reaching faceplate} &= \frac{10^6}{16 \times 1.2^2} \times T \\ \text{of image intensifier} & \\ \text{(see section 3)} & \\ &= 3.25 \times 10^4 \text{ photons cm}^{-2} \text{ sec}^{-1} \\ &[ = 6.67 \times 10^{-9} \text{ ft. candles (at 530 nm)}] \end{aligned}$$

$$\begin{aligned} \text{Effective gain (photon gain)} &= 5 \times 10^4 \times \frac{1}{4} \\ &= 1.25 \times 10^4 \end{aligned}$$

$$\begin{aligned} \text{Therefore Output*} &= 3.25 \times 10^4 \times 1.25 \times 10^4 \\ &= 4.06 \times 10^8 \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \\ &[ = 2.62 \times 10^{-4} \text{ ft. lambert (referred to 530nm)}] \end{aligned}$$

After relay lenses, illuminance\* at the detector plane is given by

$$\begin{aligned} &4.06 \times 10^8 \times .174 \times t \\ &= 5.31 \times 10^7 \text{ photons cm}^{-2} \text{ sec}^{-1} \\ &[ = 1.09 \times 10^{-5} \text{ ft. candles (referred to 530 nm)}] \end{aligned}$$

\*Note: These photons will actually have a spectral distribution determined by the output phosphor.

Thus the effective photon gain of the complete system i.e. the ratio of no. of photons reaching detector faceplate to no. incident on image intensifier faceplate

$$\begin{aligned} &= \frac{5.31 \times 10^7}{3.25 \times 10^4} \\ &= 1.63 \times 10^3 \end{aligned}$$

#### 4.3.2. Noise considerations

a) Thermal. A typical noise equivalent input for a 2nd Gen image intensifier is  $\approx 10^{-11}$  lumen  $\text{cm}^{-2}$  (referred to a 2854°K source),  
 $\approx 10^{-8}$  ft. candles.

From above, 1R at 530 nm corresponds to  $6.67 \times 10^{-9}$  ft. candles reaching the faceplate. Therefore, thermal noise is approximately equivalent to

$$\frac{10^{-8}}{6.67 \times 10^{-9}} \times \frac{\text{manufacturer's gain}}{\text{photon gain}}$$
$$\sim 6 R$$

(this noise could be essentially eliminated by moderate tube cooling).

b) Statistical. To obtain a useable picture, the final detector must receive enough photons so that the signal/noise ratio exceeds  $\sim 2:1$  for each resolution element. At the very low light levels that we are considering, we are essentially photon limited, so the statistical noise situation is determined by the number of photoelectrons generated at the image intensifier cathode and the number of resolution elements.

Assuming 1R of input, 256 x 256 resolution elements, and 15% quantum efficiency, then the number of photoelectrons generated per resolution element of the image intensifier cathode

$$= \frac{3.25 \times 10^4 \times 0.15}{256 \times 256}$$

$$= .074 \text{ per resolution element per sec.}$$

Thus to achieve 4 photoelectrons per resolution element per sec, (S/N = 2:1) we need an input of  $\sim 54R$  sec (eg 54R integrated for 1 sec). It is clear then that we are in a photon limiting situation, and the noisiness of the final picture is independent of system gain (provided the gain is sufficient so that each photoelectron results in a measurable light output pulse at the final detector). This calculation illustrates that it is essential to have time integration at the final detector in order to obtain a usable picture at these high levels.

Given that fact, final sensitivity is determined by acceptable time resolution and the maximum time the final detector can effectively integrate.

#### 4.3.3 Final Detection:

Consider three cases for the final detector: film, a TV camera, and a CCD array. Consider a source of 20R, which is a desirable limiting sensitivity in many auroral/airglow applications.

a). Film. Film is often used as a final detector because it is simple to use, has high resolution and can integrate exposures for long periods. (In this case the resolution is unimportant because limiting resolution is determined by the image intensifier). The "quantum yield" for fast films is  $< 1\%$  i.e. only 1 in 100 quanta results in a photographic effect, but this effect is cumulative so long integrations are possible.

For a 20R source, the illuminance reaching the film is (see 4.3.1 above)

$$\begin{aligned} &= 20 \times 5.31 \times 10^7 \text{ photons cm}^{-2} \text{ sec}^{-1} \\ &= 3.97 \times 10^{-3} \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ (at 530 nm)} \end{aligned}$$

For a usable film density, KODAK curves for Tri-X (400 ASA) show that

required illuminance is	$> 5 \times 10^{-3} \text{ lux sec}$
	$= 5 \times 10^{-7} \text{ lumen cm}^{-2} \text{ sec}$
	$= \frac{5 \times 10^{-7}}{680 \times .862} \text{ W cm}^{-2} \text{ sec at 530 nm}$
	$= 8.5 \times 10^{-3} \text{ erg cm}^{-2}$
Therefore, Required exposure	$= \frac{8.5 \times 10^{-3}}{3.97 \times 10^{-3}}$

$$\sim 2.1 \text{ sec}$$

which conveniently matches the required integration times for acceptable picture quality (see 4.3.2.b above). Thus fast film ( $> 400$  ASA) is ideally suited as a final detector for this situation.

b). TV Camera. If we assume 256 x 256 resolution elements for the TV faceplate (the same as assumed for the image intensifier, see 4.3.2.b. above),



then for a 20R source, the numbers of activations of each resolution element per TV field (1/60 sec) is given by

$$\begin{aligned} & 0.74 \times 20 \times 1/60 \\ & = .025 \end{aligned}$$

i.e. only 1 in 40 resolution elements of the TV faceplate will be activated in each TV field.

However, each activation will be created by a light pulse of  $1.63 \times 10^3$  photons (see 4.3.2.b above), or as high as  $\sim 6 \times 10^3$  photons if fibre optics coupling is used instead of relay lenses. This range is about the input photon equivalent of amplifier noise in most TV camera electronics. Thus to detect these pulses in real time requires either

- (i) additional external amplification eg. by adding a low-gain intensifier to the system
- (ii) use of a TV camera with an integrated intensifier stage.

The required sensitivity of the TV camera detector is found by calculating the faceplate illuminance if all resolution elements received this number of photons ( $1.63 \times 10^3$ ) in 1/60 sec. If we assume a 16mm diag. faceplate ( $1.25 \text{ cm}^2$  picture area) then this illuminance is  $\frac{1.63 \times 10^3 \times 256 \times 256 \times 60}{1.25}$  photons  $\text{cm}^{-2} \text{ sec}^{-1}$

$$\begin{aligned} & = 5.2 \times 10^9 \text{ photons cm}^{-2} \text{ sec}^{-1} \\ & = 1.05 \times 10^{-3} \text{ ft. candles (referred to 530 nm)} \\ & \sim 2.5 \times 10^{-4} \text{ ft. candles (referred to 2854°K)} \end{aligned}$$

But because only 1 in 40 resolution elements are activated each field, the picture would be unusable. The TV camera must integrate for 2.7 sec. to give 4 activations per resolution element (S/N of 2:1).

Thus we require a LLL TV camera with a quoted manufacturer's sensitivity of  $\sim 2.5 \times 10^{-4}$  ft. candles, and a capability of integrating effectively for  $\sim 2.7$  sec. The first requirement is readily met by many LLL TV cameras, but the

intergration requirement is only possible with special tube types, such as the SEC type of camera, and moderate detector cooling may be desirable.

c). CCD array. In general, similar comments apply as those discussed for the TV camera. Typical arrays have more than adequate sensitivity, but the integration requirement still holds. Because of the noise levels of CCD arrays, cooling is necessary to achieve 2-3 sec integration times. Required cooling is moderate,  $\sim -30^{\circ}\text{C}$ . The cooled CCD array however, has significant advantages over film and the TV camera, in that exhibits less distortion, it can handle a much larger dynamic range, and its output is much more linear with light input.

##### 5. Maximizing Sensitivity.

It is clear from the above discussion that the limiting factor in LLL performance is not detector gain, but photon noise limitations at the input photocathode. Once a photoelectron is generated at the input, current image intensifier and TV tube technology ensures that a light pulse will be detected and displayed at the output.

The only way to improve input photon limitations are to

- a) increase efficiency of collecting optics.
- b) Increase photocathode quantum efficiency. This might be achieved by selecting photocathodes for particular spectral regions, but in general the S-20 and its variants are the most suited for auroral/airglow research. Gallium arsenide photocathodes may be more suited for surveillance applications.
- c) Use a minifying image intensifier (with the same output screen resolution). For example, a  $40\text{mm} \times 25\text{mm}$  image tube results in an increase in cathode collecting area of  $\sim 2.5$  for each resolution element of the output screen. Such intensifiers are available in 1st Generation types, but significant minification is not yet available in

2nd Gen tubes. (Note too that suitable input optics must be available to use the larger input area at a similar F number to the non-minified system).

6. Manufacturer's "Sensitivity".

To obtain a usable picture ( $S/N = 2:1$ ) in real time, the above discussion shows that the source integrated emission rate would have to be 3.2 kR. This might be reduced to  $\sim 2\text{kR}$  with faster input optics, which corresponds to  $\sim 10^{-5}$  ft. candles faceplate illumination (see 4.3.1). These numbers are referred to a 530nm source, and would be reduced to  $\sim 2.5 \times 10^{-6}$  ft. candles for the 2854°K source usually used by tube manufacturers.

This faceplate illuminance represents the limit for obtaining a useable picture ( $S/N = 2:1$ ) at a resolution of  $256 \times 256$ . One should view quoted manufacturer's sensitivities which are less than this number with some scepticism, as lower numbers imply one or more of the following

- (i)  $S/N$  ratio less than 2:1
- (ii) resolution less than  $256 \times 256$
- (iii) extended red cathode sensitivity (which increases the response to a 2854°K light source, but does not affect the number of lumens contributing to faceplate illuminance).
- (iv) a test light source "redder" than a 2854°K source
- (v) effective integration by the eye (at low light levels, the human eye effectively integrates for  $\sim 0.1$  sec, and so a picture might be judged "usable" in some situations by a human observer, whereas individual TV frames would not be judged usable.
- (vi) effective integration by tube lag effects for some types of TV tubes.

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